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MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO) 06 May 2002

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-VG-2002-096**
Andrew Ketsdever (PRSA), "Free Molecule Micro-Resistojet: Current Status"

ESA Micropropulsion Workshop **(Statement A)**
(29-30 May 2002, La Spazia, Italy) **(Deadline: 29 May 2002)**

1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement, b.) military/national critical technology, c.) export controls or distribution restrictions, d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.
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PHILIP A. KESSEL Date
Technical Advisor
Space and Missile Propulsion Division

Free Molecule Micro-Resistojet: Current Status

Dr. Andrew D. Ketsdever
Air Force Research Laboratory
Propulsion Directorate

Micropropulsion Workshop

29-30 MAY 2002, La Spezia, Italy

Introduction

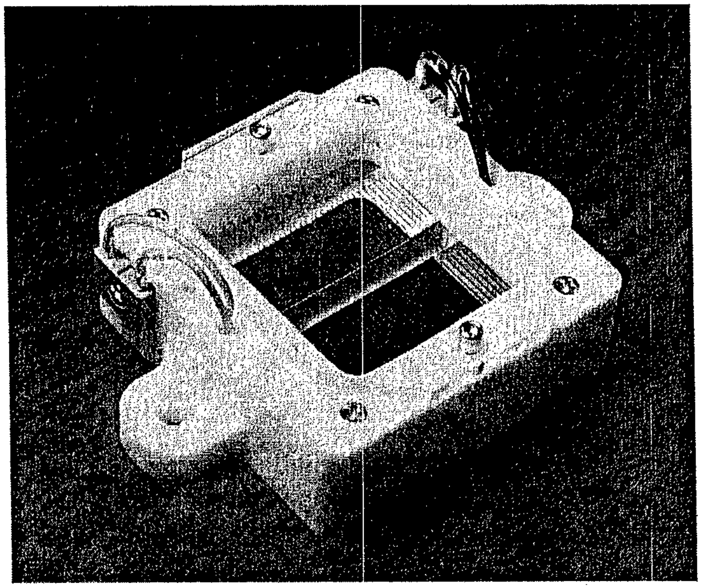
- Collaboration
  - AFRL, Edwards

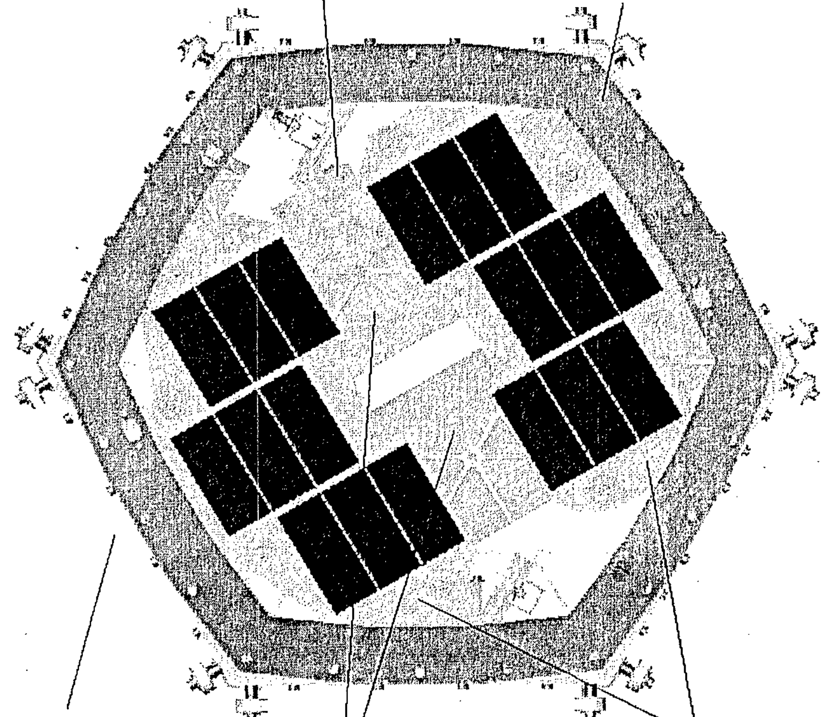
    Hardware + Testing facility
  - Microdevices Lab, JPL

    Fabrication of FMMR heater chips
  - Arizona State University

    Characterization of FMMR heater chips (ground & space)+ Spacecraft bus
- Hardware delivery
  - Instrument(2 units) *July, 2001*
  - 3CS Constellation (3 S/C) *December, 2001*
- Target 2003 flight on Shuttle

Flight-Test

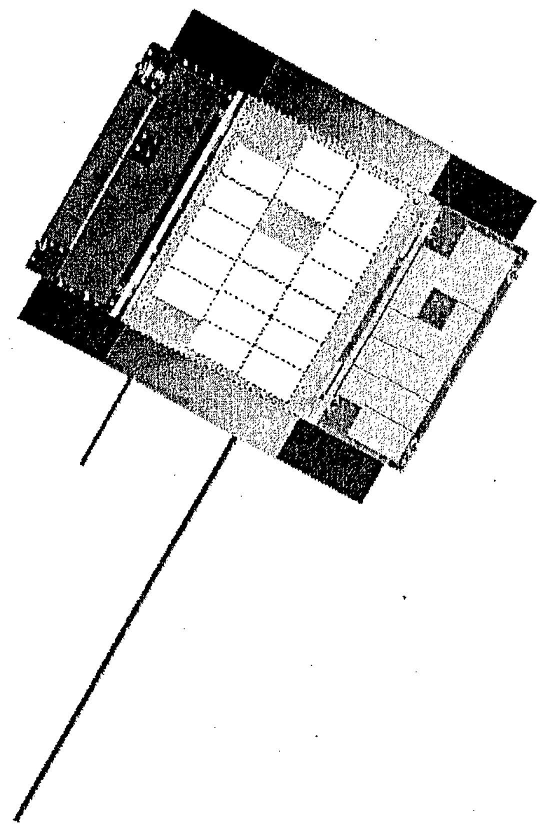




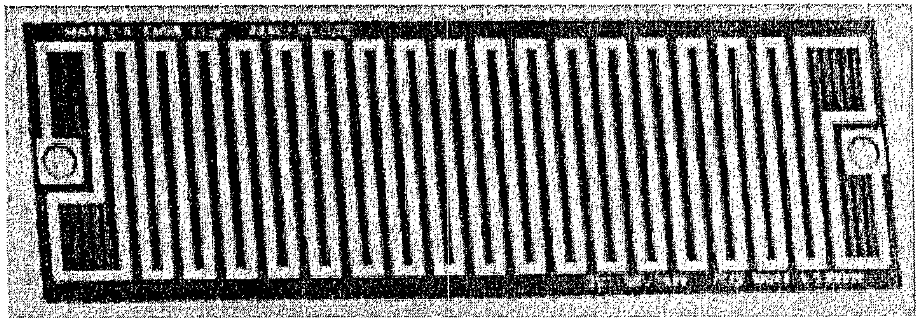
- 2 FMMR chips in a Teflon housing
- 80grams, 5 x 7 x 2 cm
- ~600K max.
- 2W nom., 5W max. per chip

Flight-Test

- Objectives
  - Chip survivability
    - Launch
    - LEO environment
    - Thermal Cycling
  - Operation characteristics
    - Power consumption
- Operation
  - Min. 10-min per orbit
  - Voltage and current consumed
  - Min. 1Hz frequency

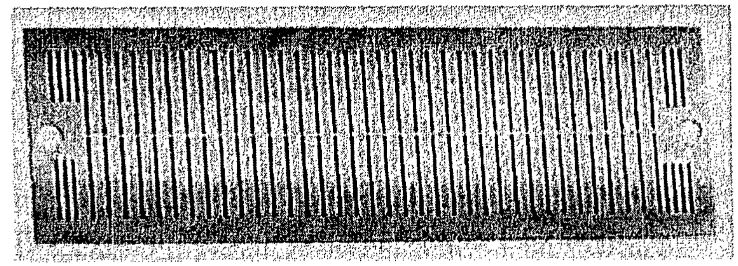


FMMR Characteristics

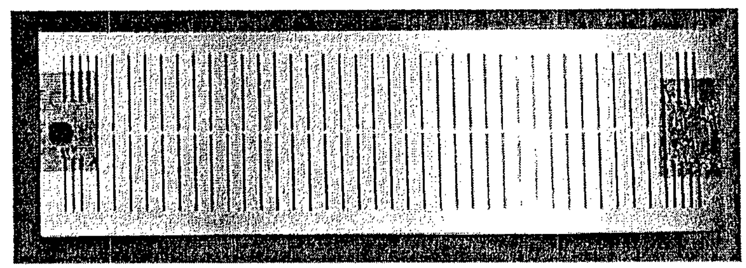


- 13 x 42mm, 400μm-thick LSN wafer
- Heater
  - Cr (300Å) + Pt (600Å) + Au (8000Å)
  - 400μm wide, 0.45m total length
- Expansion slots
  - 50 slots
  - 100μm wide, 3 to 5mm long

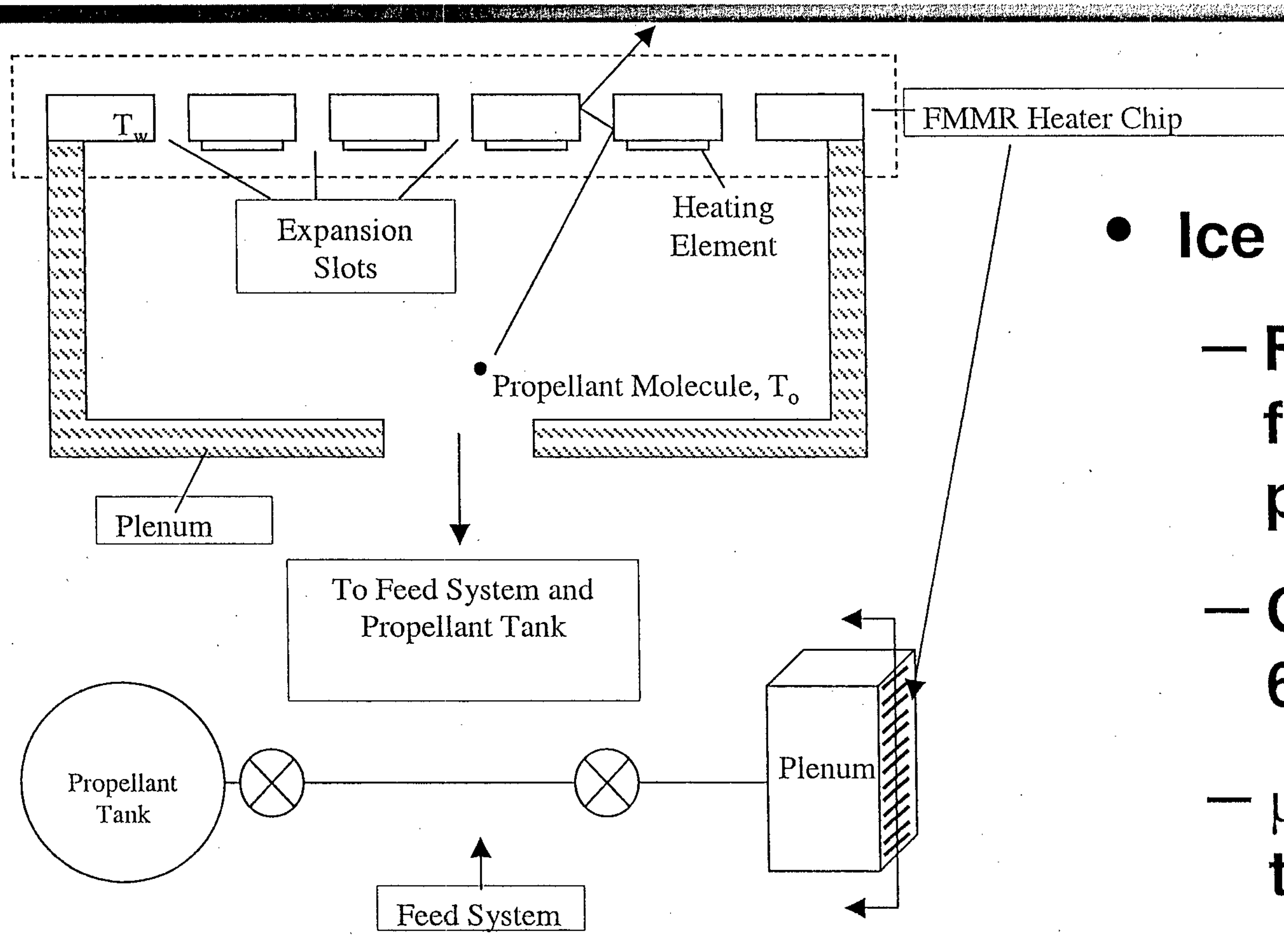
5000Å Si_3N_4, ε~0.5



8000Å Gold , ε~0.02



FMMR Concept



- Ice propellant
  - Free molecular flow at ice vapor pressure
  - Optimal Tw ≈ 600K
  - μN to 10's mN thrust

$$Thrust = \frac{n_p k}{2} \sqrt{T_w T_o} A_s$$

Heat Transfer Theory

$$\dot{E}_{in} + \dot{E}_{generated} = \dot{E}_{out} + \dot{E}_{stored}$$

$$0$$

Joule Heating $Q_{Joule} = (dV)_{element} I$

Heat stored $Q^{st} = \left(\rho c_p \frac{\partial T}{\partial t} \right) \Delta x \Delta y \Delta z$

Irradiation $Q_{rad} = \varepsilon \sigma (T^4_{element} - T^4_{env}) A_{element}$

Conduction $Q_{cond} = \left(\frac{\partial}{\partial x}\left(\kappa_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y}\left(\kappa_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z}\left(\kappa_z \frac{\partial T}{\partial z} \right) \right) (\Delta x \Delta y \Delta z)$

$$\left(I^2 R_{element} - \varepsilon \sigma (T^4_{element} - T^4_{env}) A_{element} \right) \frac{1}{\Delta Vol} + \kappa \nabla^2 T_{element} = \left(\rho c_p \frac{\partial T_{element}}{\partial t} \right)$$

FMMR Experiment

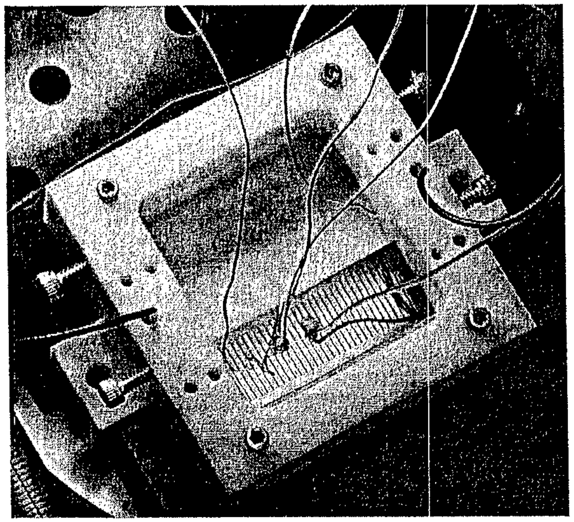
- Objectives
  - Background pressure sensitivity

Chip	*Nitride*
Pressure	*1e-4 to 1e-6Torr*
Power Supply	*15VDC*
Environment T°	*Room*

  - Surface temperature and power consumption

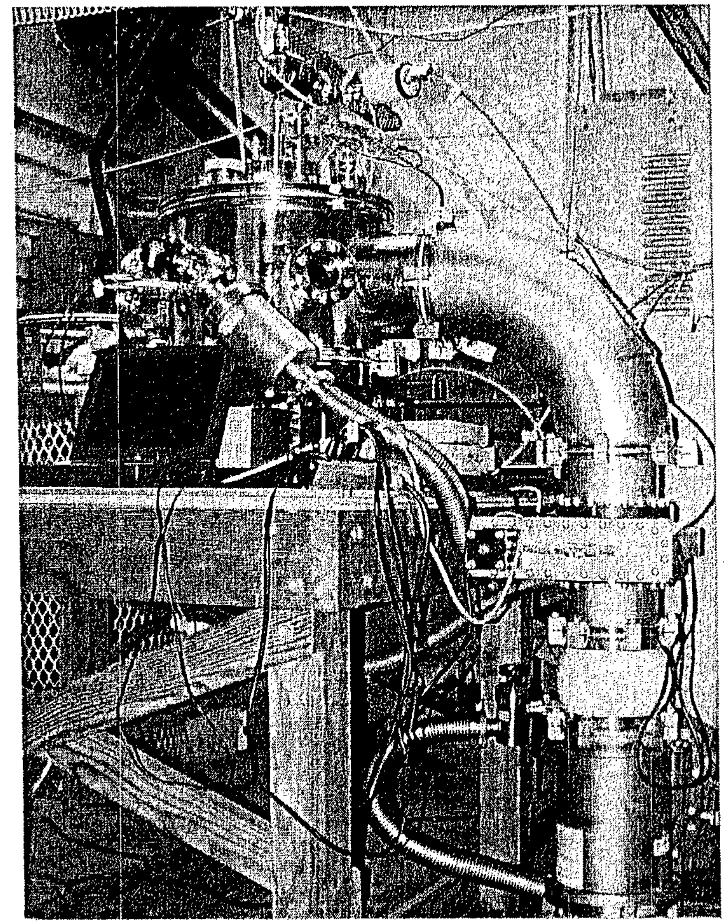
Chip	*Nitride, Gold*
Pressure	*1e-6Torr*
Power Supply	*5, 7.5, 10, 12, 13.5, 15VDC*
Environment T°	*Room, LN2-cooling*

FMMR Experiment Setup

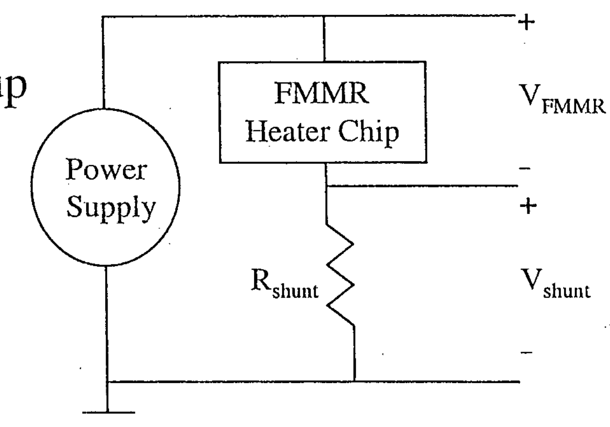


⇐ Nitride chip test setup

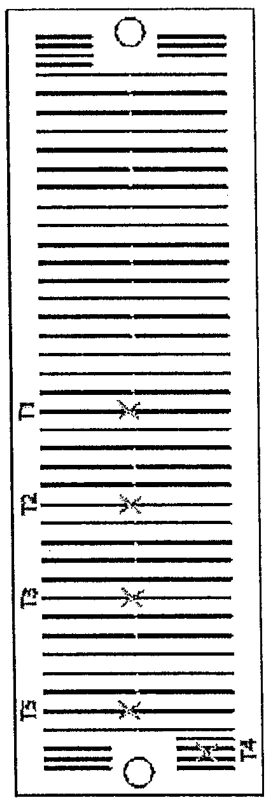
Vacuum chamber ⇒



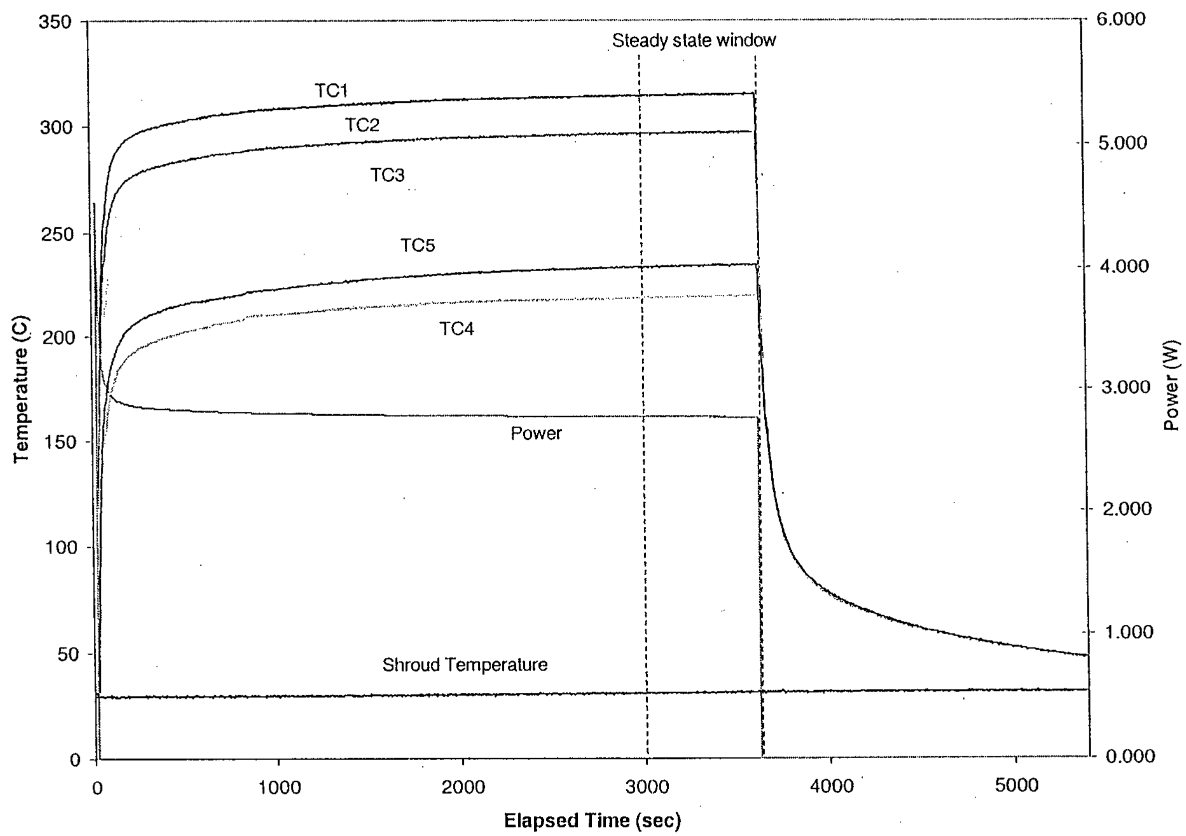
Experiment setup schematic ⇒



FMMR Experiment Results
Typical Temperature Profile

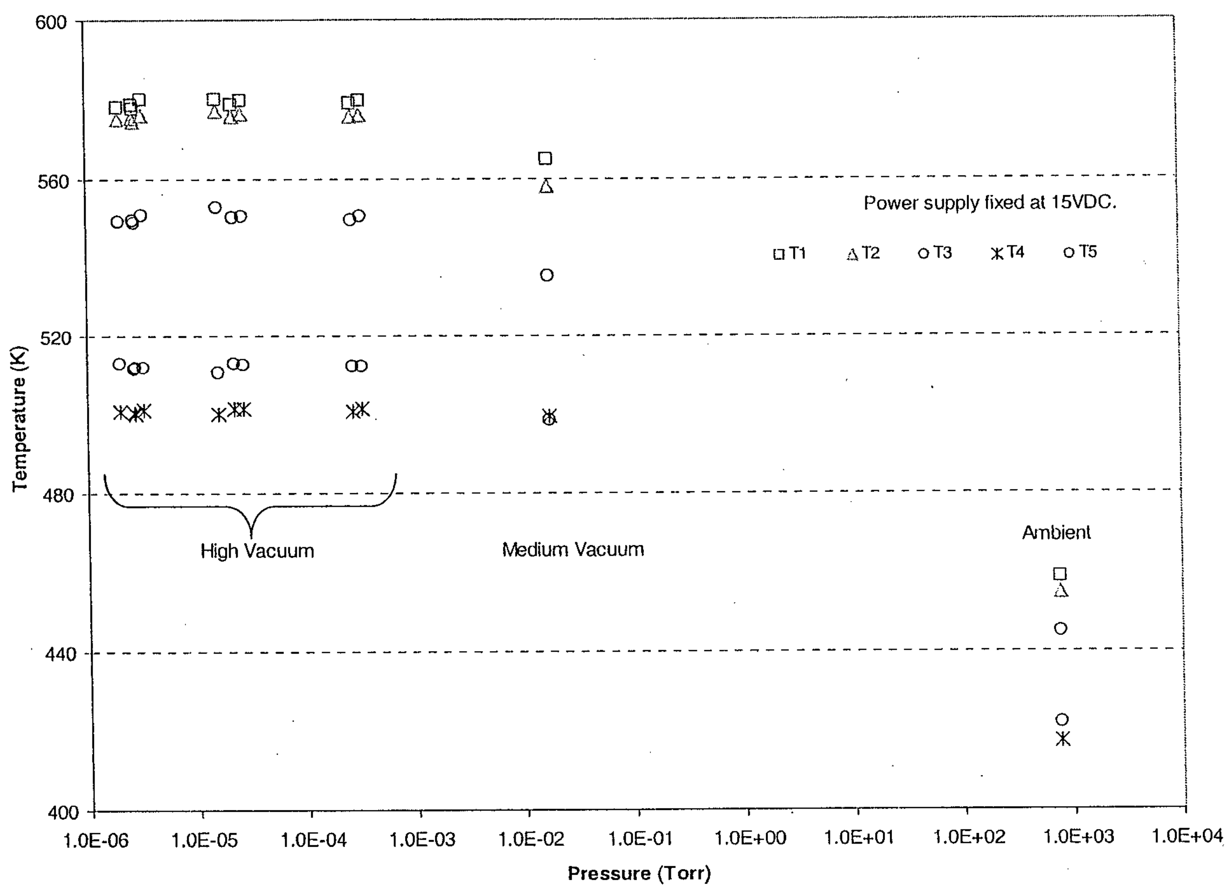


Nitride Chip Characteristics vs. Time (2.0e-6 torr; 60/90 cycle; 14.95VDC)

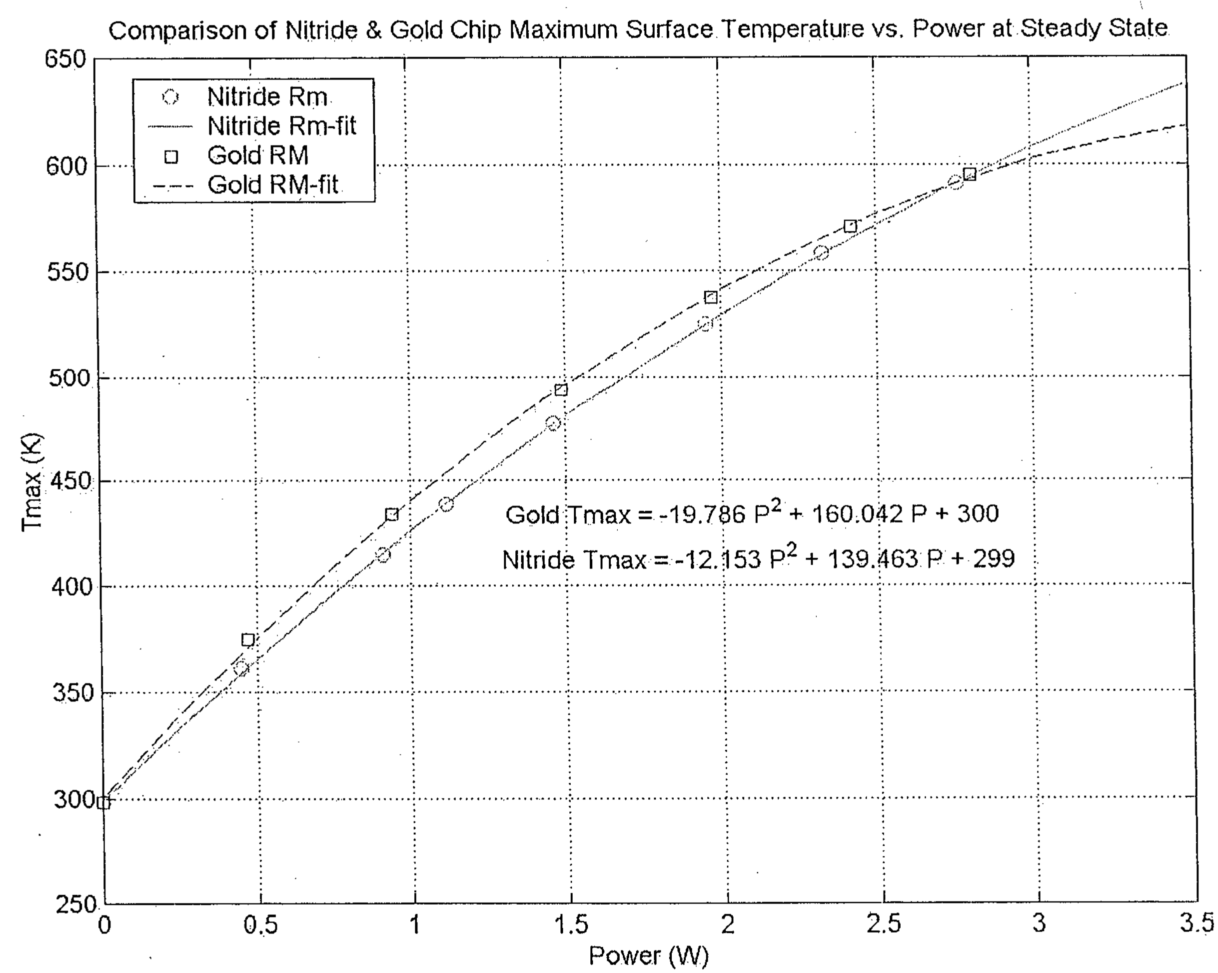


FMMR Experiment Results
Background Pressure Sensitivity

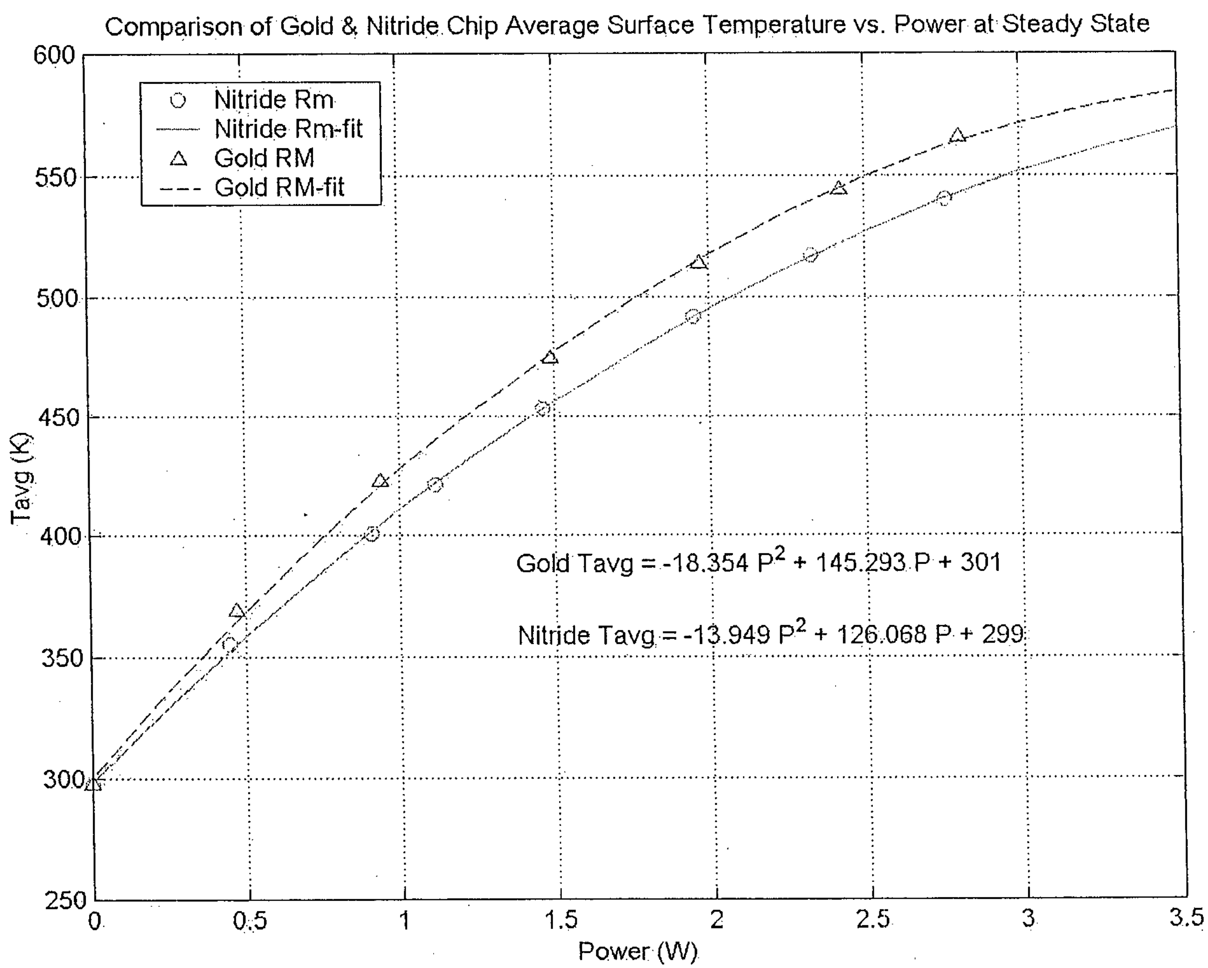
Nitride Chip Surface Temperaure vs. Background Pressure



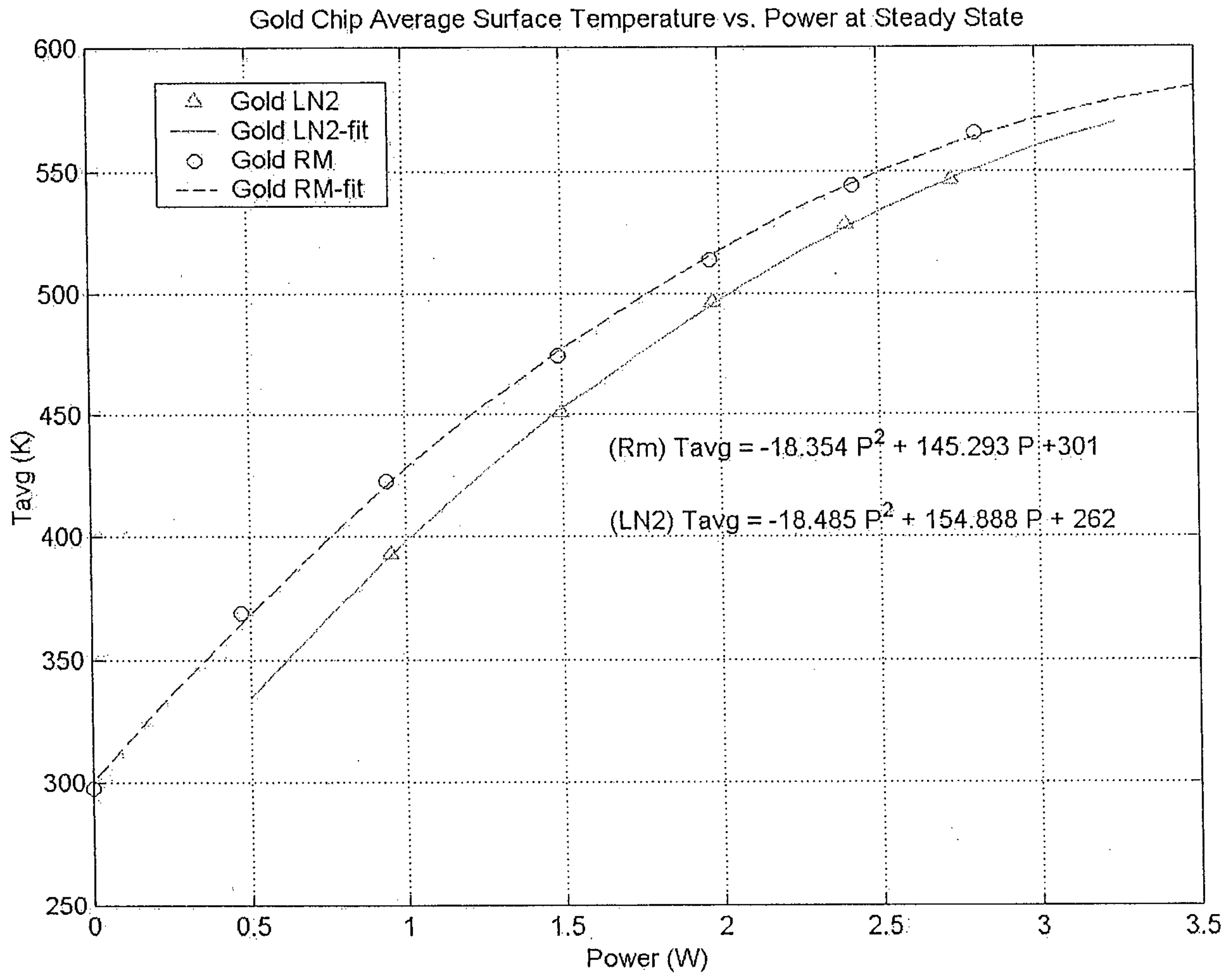
FMMR Experiment Results
High Vacuum Power Variation



FMMR Experiment Results
High Vacuum Power Variation



FMMR Experiment Results
High Vacuum Power Variation

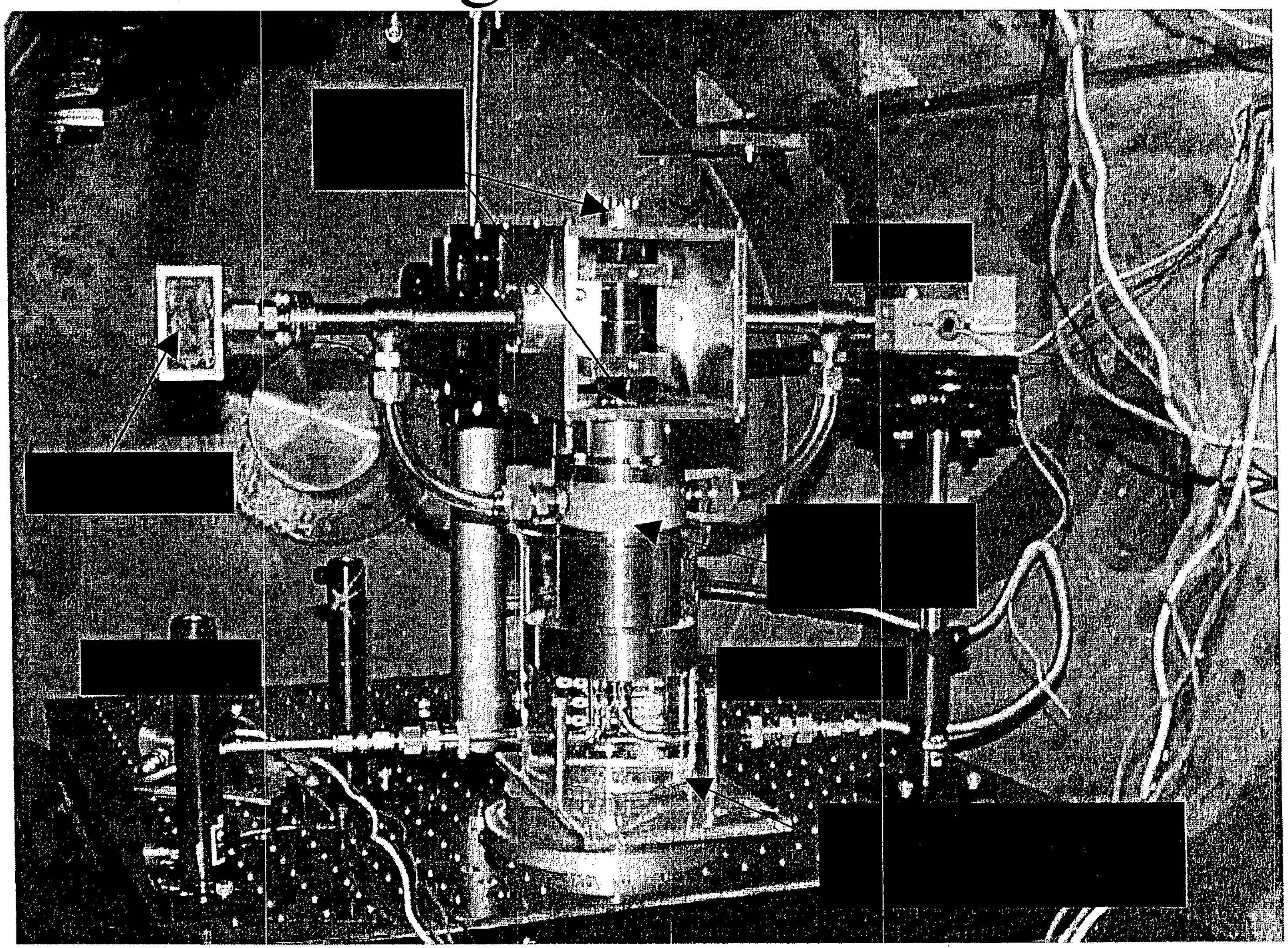


FMMR Experiment Results
Summary

- Flight Experiment will collect FMMR heater chip surface temperature as a function of input power
- Predicted heat transfer environment
  - Vacuum chamber pressure < 1e-4Torr to eliminate convective heat transfer
  - Liquid nitrogen shroud for proper radiative prediction
- Longitudinal temperature distribution
  - Gradient is more pronounced on the nitride chip
  - Gold chip is more power efficient
- To reach Tmax~600K
  - Nitride: 2.90W
  - Gold: 2.95W

nano-Newton Thrust Stand

Current Configuration in CHAFF-II

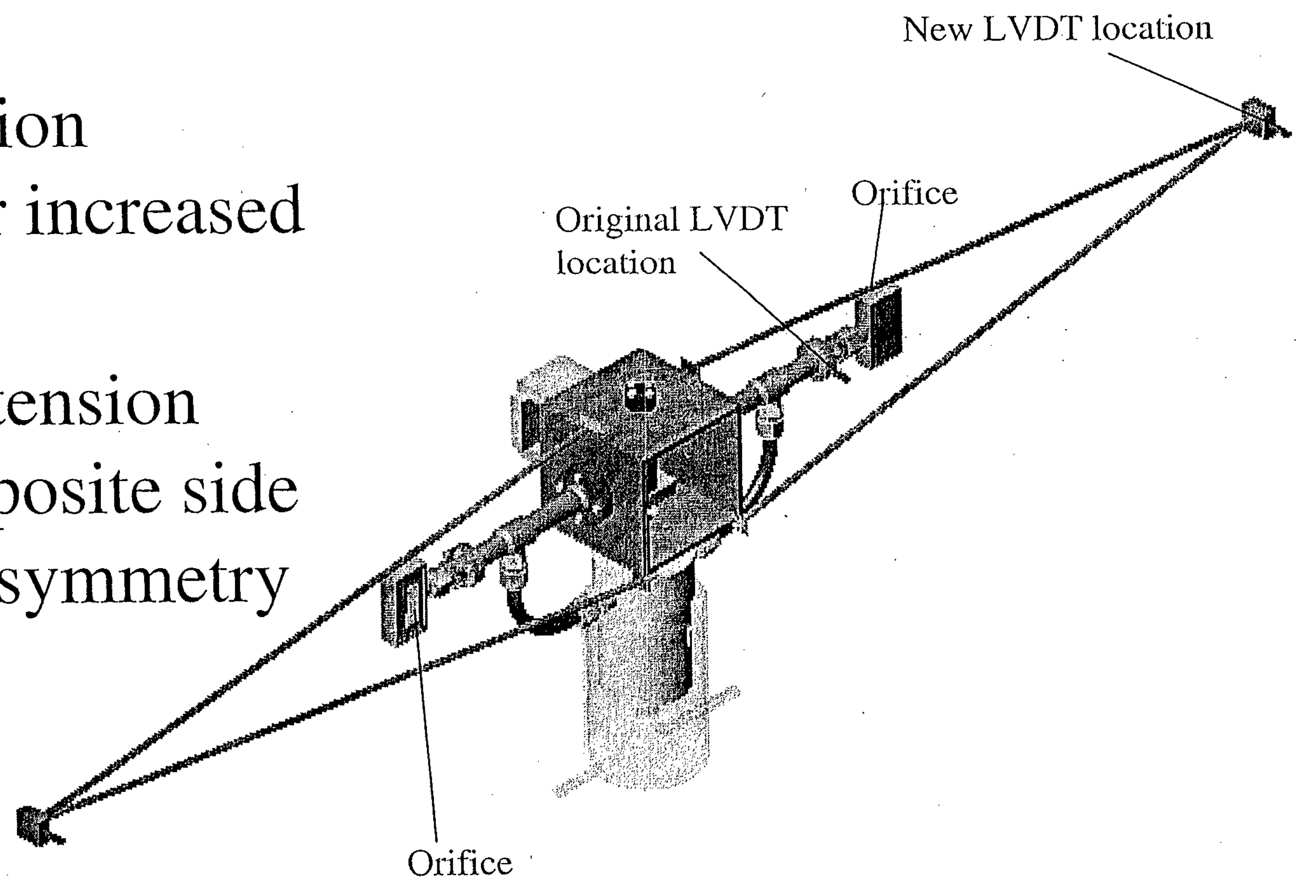


Chronology

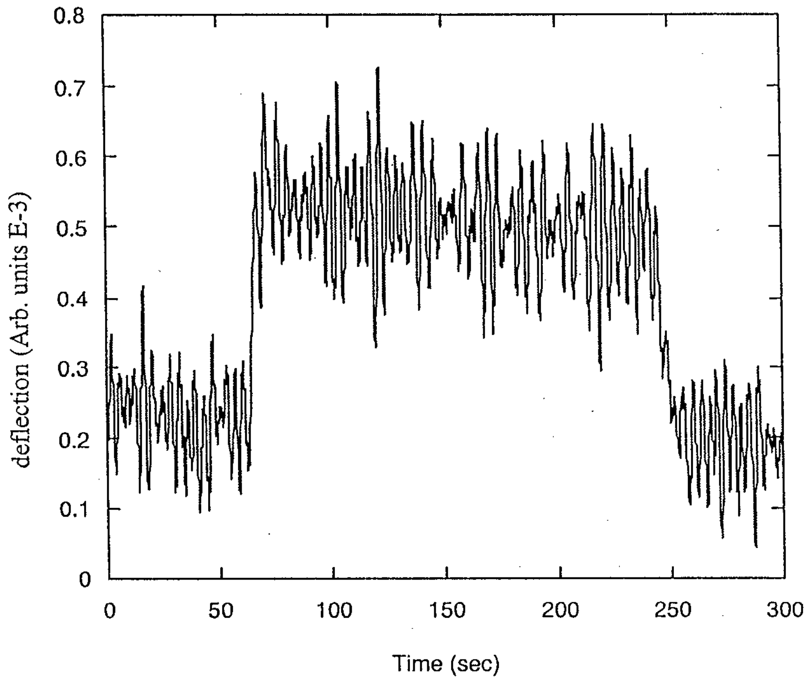
- Measured thrusts from 1 mN to 5 μN in CHAFF-II facility. (2000)
- Moved thrust stand to CHAFF-IV (Lower environmental noise and background pressures.)
- Measured thrusts down to 500 nN. (Early 2001)
- Extended thrust stand arms for increased deflection. (Mid 2001)
- Thrusts measured down to 90 nN. (Mid 2001)

nNTS Arm Extensions

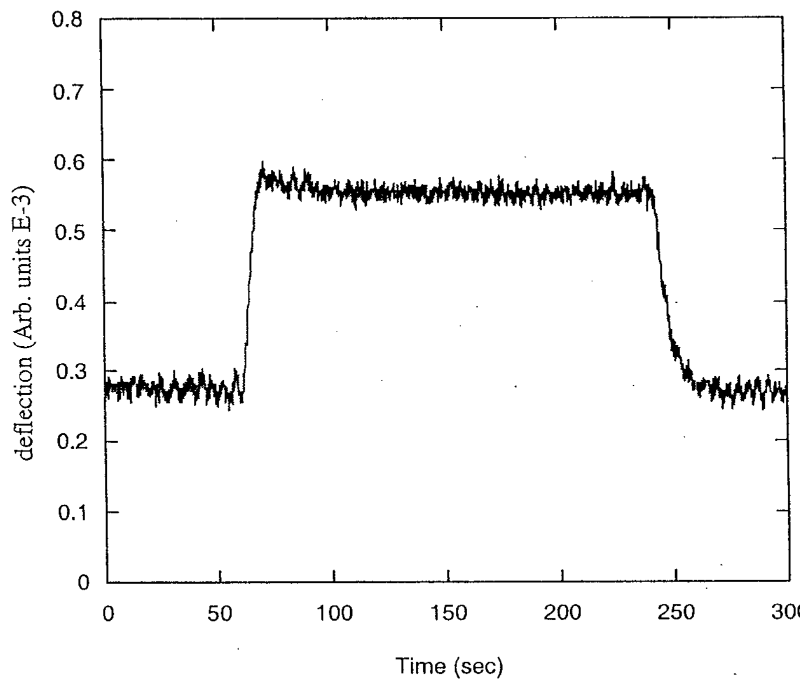
- LVDT location extended for increased deflection
- Identical extension added to opposite side to maintain symmetry



Thrust Stand Traces (~700 nN)



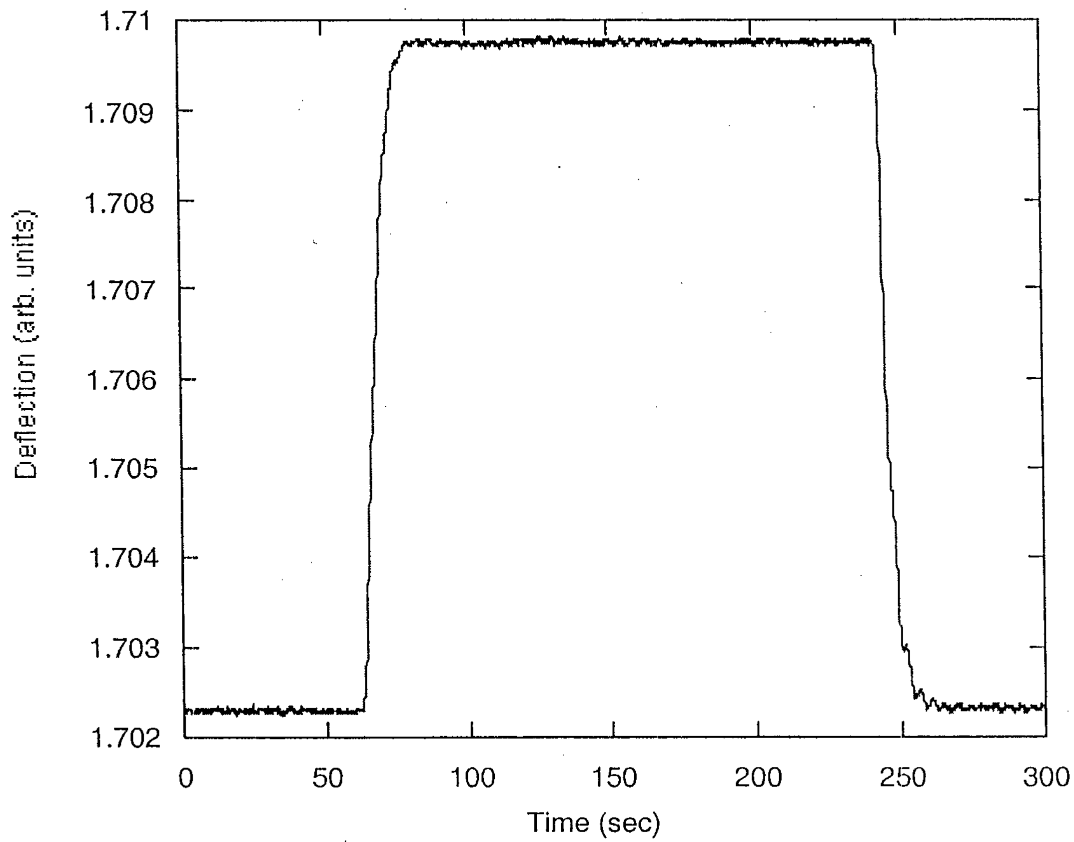
Thrust stand trace with one arm extension using nitrogen at P_0=0.007 Torr.



Trace under same conditions with both extensions

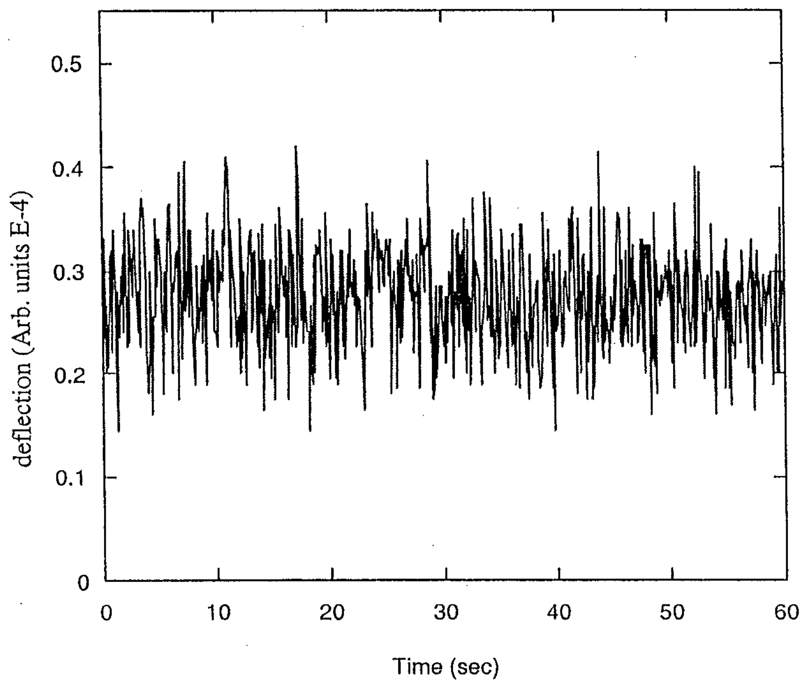
- Mass balancing and symmetry appear to have a significant impact upon the environmental noise of the system.

μN Level nNTS Trace

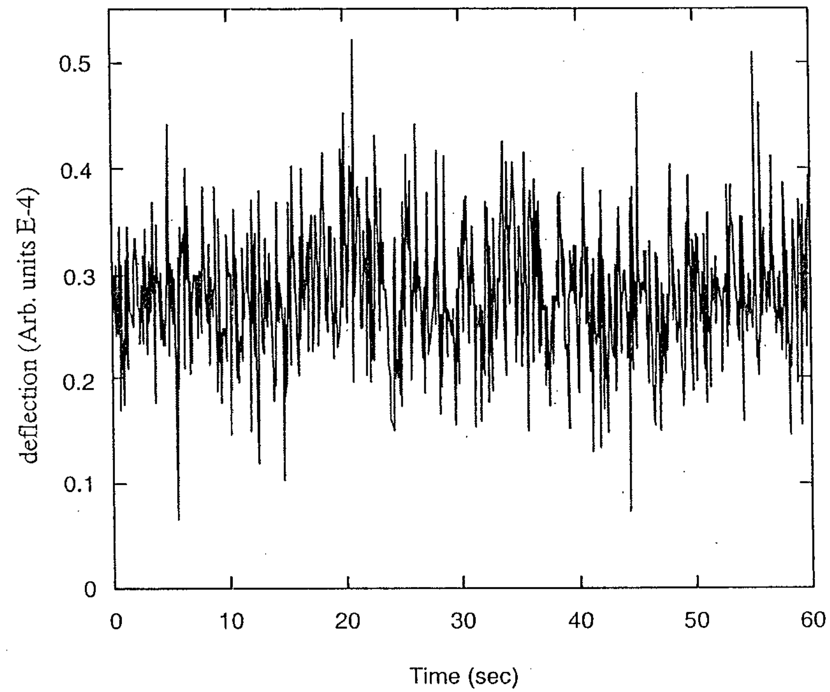


8 μN trace for nitrogen gas.

Noise Contributions



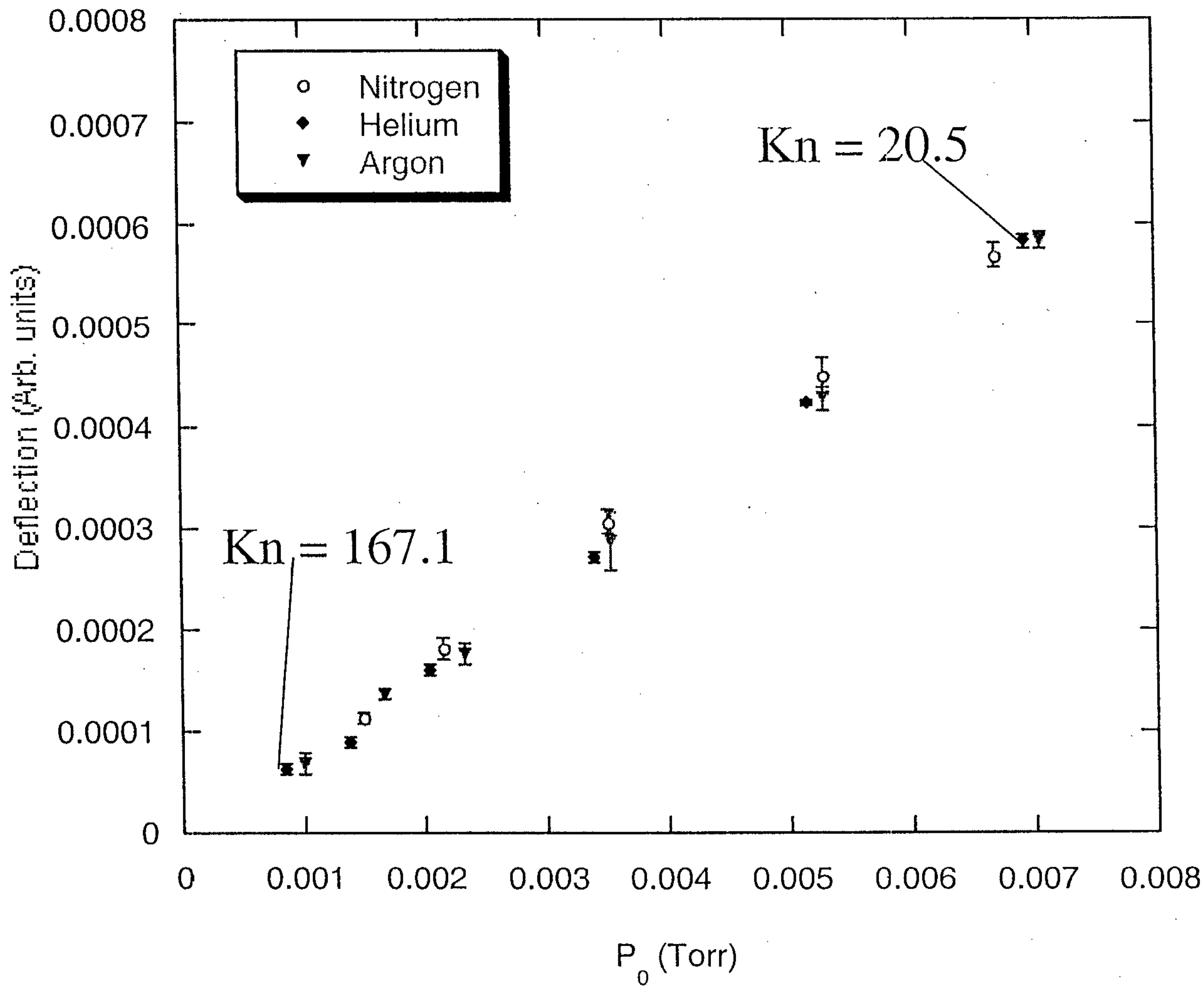
Noise produced by the 24-bit data acquisition system.



Noise from data system and environmental noise from the LVDT connected to the nNTS.

- Majority of noise is from the data acquisition system.

Deflection Measurements



Deflection versus stagnation pressure for nitrogen, helium, and argon

Calibration Techniques

- Direct Simulation Monte Carlo technique for high Knudsen numbers.
  - Experimentally determined Helium data used for stagnation pressure, temperature, and mass flow boundary conditions
  - To approach free molecule conditions, data used had large Kn.
  - DSMC calculations performed by A. Alexeenko and Prof. D. Levin at Penn State University.
- Analytical
  - Uses equations based on free molecular theory to verify available DSMC results.

Orifice Flow Theory

- Analytical equations for free molecule (collisionless) flow:

$$\Im_{fm} = \alpha \frac{p_o}{2} A_o$$

$$\dot{M}_{fm} = \alpha m \frac{n_o \overline{c'}}{4} A_o = \alpha m n_o \frac{\sqrt{\frac{8kT_o}{\pi m}}}{4} A_o$$

$$Isp_{fm} = \frac{\sqrt{\frac{\pi}{2}\frac{k}{m}T_o}}{g}$$

- Plenum and orifice design contribute to departures from the analytical model. Three primary contributors:

Effect of Drift Velocity

- Incident number flux with bulk flow, c_0

$$\dot{N}_{Act} = \left(\frac{n\beta^3}{\pi^{3/2}}\right)\int_{-\infty}^{\infty}\exp(-\beta^2\omega'^2)d\omega' \int_{-\infty}^{\infty}\exp(-\beta^2 v'^2)dv' \int_{-c_0\cos\theta}^{\infty}(u' + c_0\cos\theta)\exp(-\beta^2 u'^2)du'$$

- Solution of the integral

$$\dot{N}_{Act} = \left(\frac{n}{2\beta\pi^{1/2}}\right)\left(\exp(-S^2\cos^2\theta) + \pi^{1/2} S\cos\theta\left(1 + erf(S\cos\theta)\right)\right), S = \beta c_0 = \frac{c_0}{\left(2\frac{k}{m}T_0\right)^{1/2}}$$

- For this case during calibrations, $S = 3.11\times10^{-3}$, $\theta = 49°$

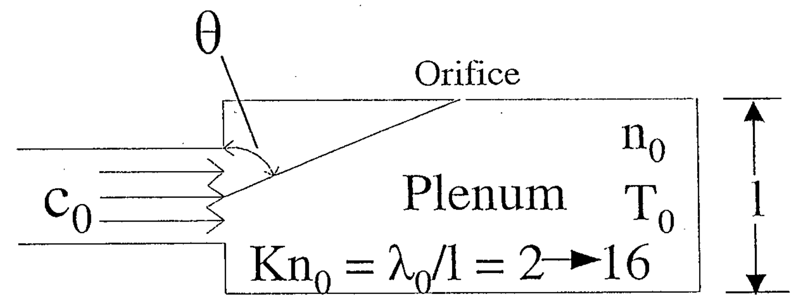
$$\dot{N}_{Act} = \dot{N}_i(1.0036)$$

- Where

$$\dot{N}_i = \frac{n_0\overline{c}'}{4}$$

is the number flux with no bulk flow

- Velocity drift increases thrust by a maximum of 0.36%.

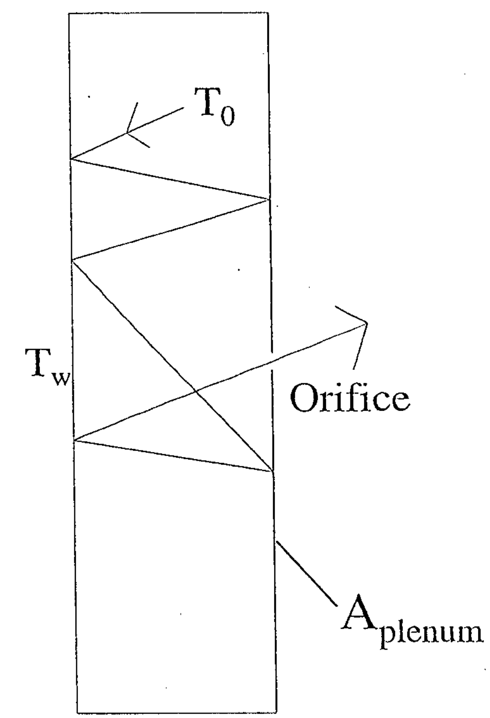


Effect of Unknown Gas Temperature

- The average number of wall collisions.

$$N_c = \frac{A_{plenum}}{A_{orifice}} = 780$$

- Assuming an accommodation coefficient of 0.5 and an initial temperature ratio of 2, a molecule has a temperature of 0.999 T_w after nine collisions

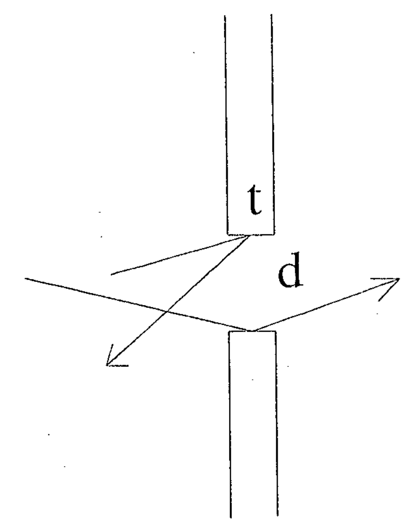


Effect of Finite Orifice Thickness

- Using the equation for number flux an approximation for the effect of the finite orifice thickness upon the thrust can be found. For this case t = 0.015 mm, d = 1 mm.

$$\dot{N}_i = \frac{n\bar{c}'}{4}(1 - t/2d) = 0.9925\left(\frac{n\bar{c}'}{4}\right)$$

- Assuming a scenario where reflection is fully diffuse, half of the molecules that hit the wall will reflect back into the plenum, decreasing thrust by 0.75%.



DSMC versus Analytical

P_o (mTorr)	Kn	$\Im$ (nN) (DSMC)	$\Im$ (nN) (analytical)
0.85	167.1	88.88	88.98
1.38	102.9	145.1	144.4
2.05	69.3	216.2	214.6
3.39	41.9	358.4	354.9
5.15	27.6	545.2	539.1
6.93	20.5	734.1	725.5

- Comparison between DSMC and analytical solutions shows a match to within 0.2% for helium with Kn = 167.1 and less than 2% for Kn = 20.5.
- Small, anticipated effects of collisions are indicated at Kn = 20.5.

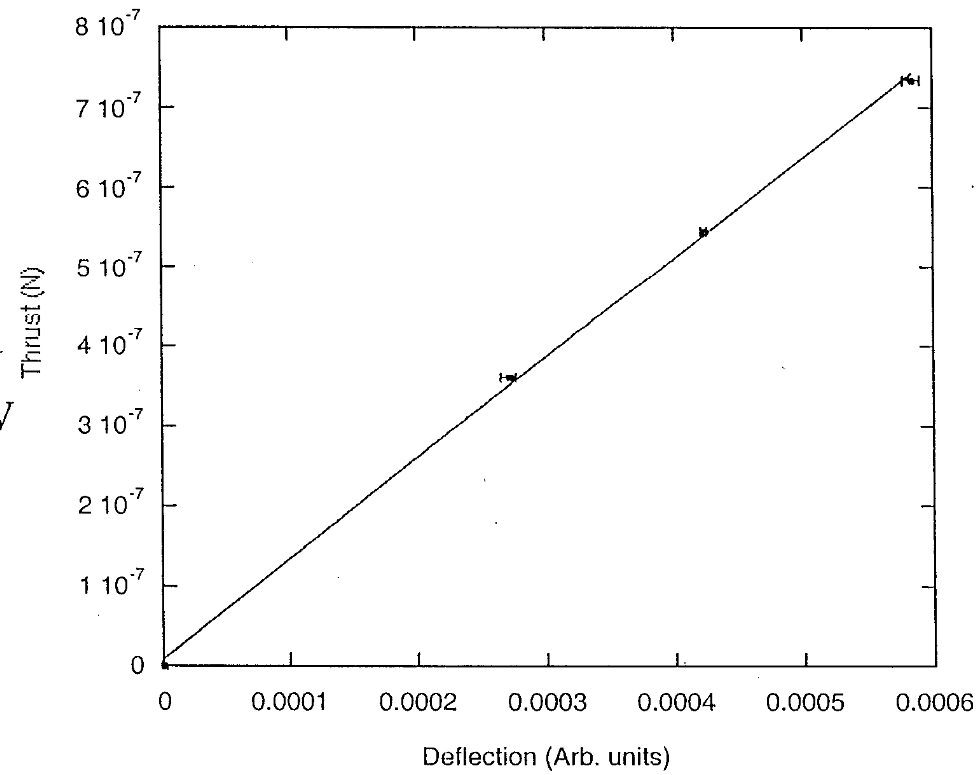
Calibration Errors

$\Im$ (nN)	DSMC calibration error		Experimental Error	
	Error in α	Error in d_o (mm)	Deflection $\pm\sigma_D$ (%)	Thrust $\pm\sigma_\Im$ (%)
88.8	0.993 ± 0.0007	1 ± 0.025	9.5	10.7
734	0.993 ± 0.0007	1 ± 0.025	1.1	2.0

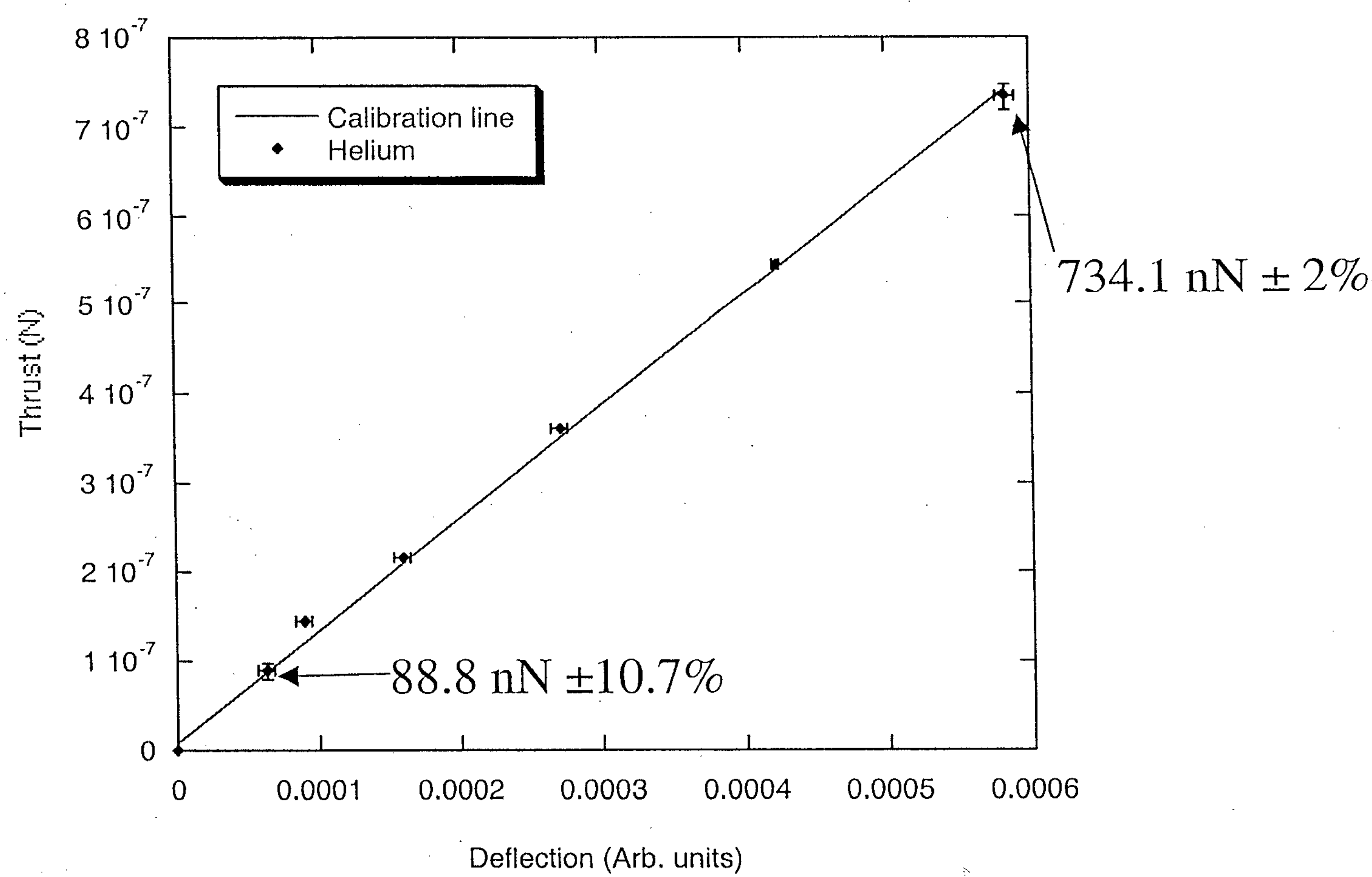
- Errors associated with the calibration methods (transmission probability, orifice diameter) and experimental error contribute to the calibrated thrust error.

Thrust Calibration Line

- Thrust determined from DSMC results.
- Calibration line determined from the most accurate (low std. dev.) helium data at high Kn



Helium Thrust Results

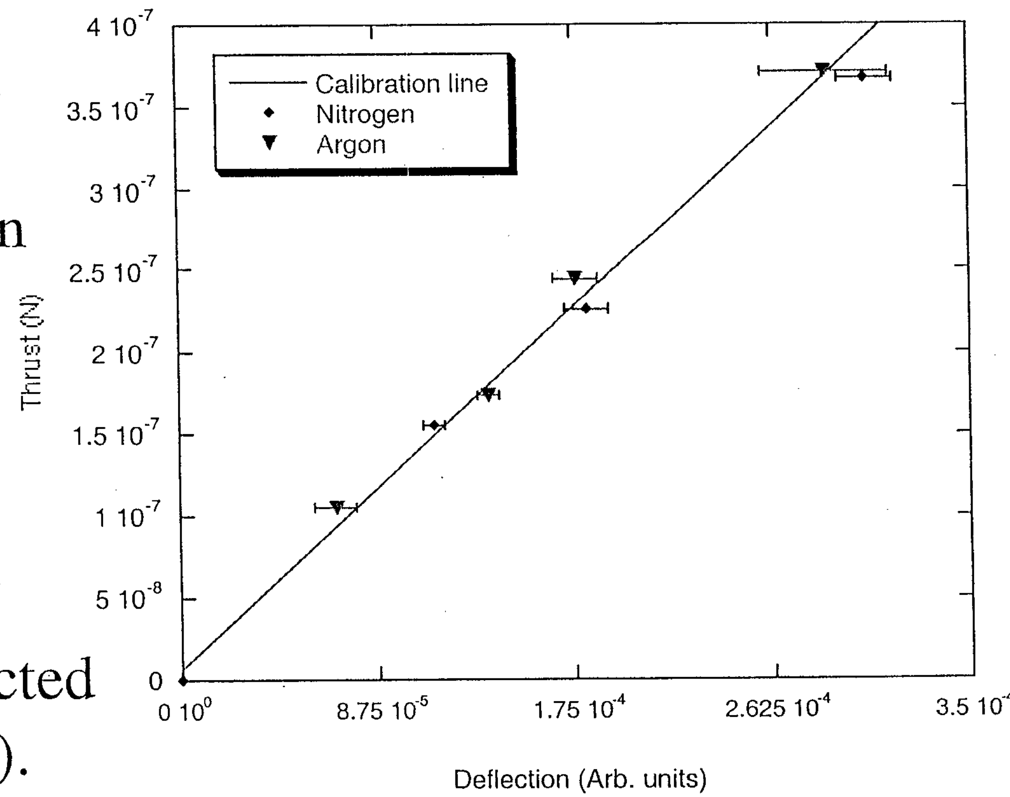


Thrust versus deflection for helium plotted with calibration line

Calibration Application

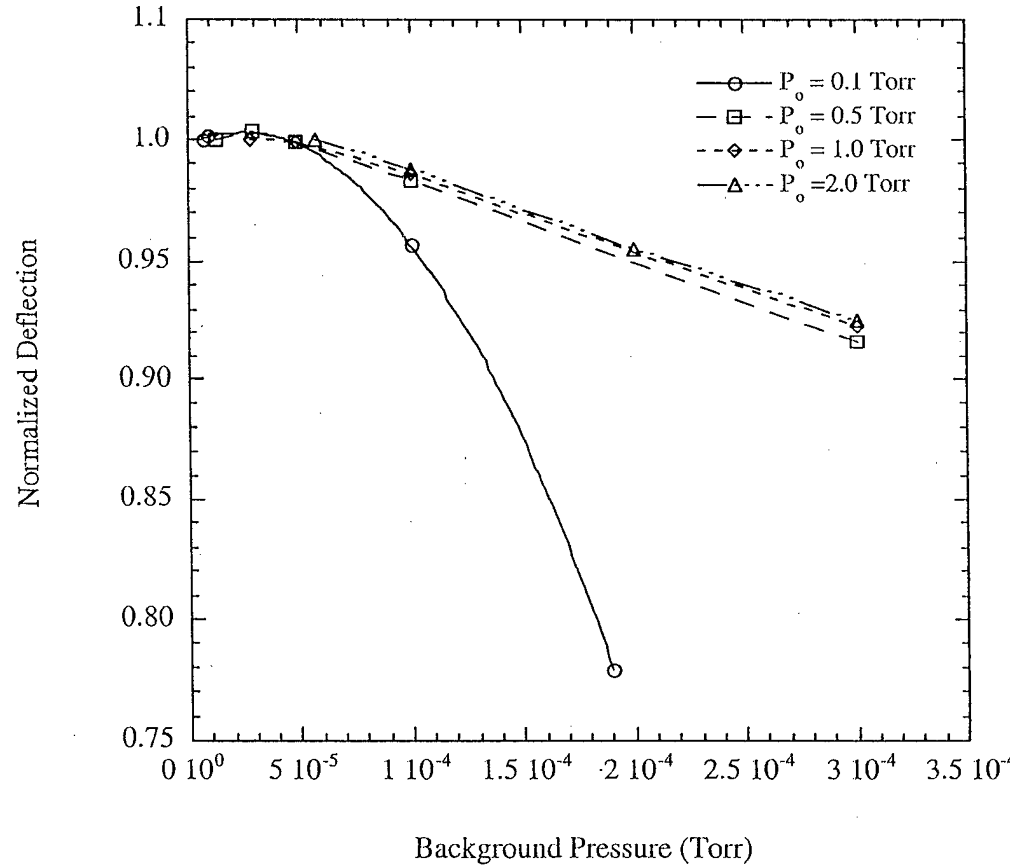
- Helium (large Kn) derived calibration line plotted against the results for argon and nitrogen gases.

- Thrust at high Knudsen numbers is shown to be reasonably independent of the type of gas used (expected from free molecule theory).



Facility Effects

- Measured deflection asymptotes at lower facility background pressures.
- For the range of stagnation pressures investigated in this study, facility background pressure remained below 1.5×10^{-5} Torr.



Normalized deflection for nitrogen as a function of facility background pressure

Conclusions

- Thrust stand calibration using near collisionless orifice flow is accurate in the nano-Newton thrust range.
- Care must be taken when using a free molecular orifice as a calibrator.
  - Small t/d required
  - Plenum design
    - Free molecular plenum – relatively high Kn.
    - Free molecule orifice – very high Kn
    - Plenum inlet area must be large compared to orifice area to minimize thrust contributions from the inlet average flow speed.
    - Average number of wall collisions must be great enough to ensure a known T_0.
- A minimum thrust of 88.8 nN ± 10.7% has been measured.
- nNTS represents a significant improvement in thrust measurements over currently published results.
- nNTS is expected to be an important diagnostic tool for micropropulsion system testing.
  - Resolution
  - Versatility
- Facility effects from changing background pressure cannot be ignored in typical micropropulsion vacuum facilities.